

SUPERCONDUCTING HOT ELECTRON MIXERS FOR FIBER OPTICS

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RESEARCH FINDINGS

I. Aims and Research Objectives

The main objective of this grant was research and development of superconducting NbN hot-electron photodevices for the optical-to-electrical signal conversion with a speed of 30 Gb/s. The program was realized as a direct collaboration between the Moscow State Pedagogical University (MSPU) and the University of Rochester (UR). As the demonstration project, we developed an integrated superconducting fiber-optic signal-processing unit, consisting a hot-electron NbN device and a broadband amplifying circuitry, operational at liquid helium temperatures. We measured the quantum photon yield of our devices, as well as their time-resolved, picosecond response. The MSPU-UR work coordination included a united research program for both groups, joint measurements in Moscow and Rochester, expeditious exchange of experimental samples and results, and electronic conferencing.

II. Long Term Goals

Navy operations are global, and require the most efficient and secure data processing and communication. Thus, ultrafast digital data processing and "unlimited" bandwidth communication, including quantum computing and quantum information, are the most crucial elements for the Navy future missions and warfare. Providing Navy with ultrafast and absolutely secure all-digital communication and data processing systems is our main long-term research goal. We decided to focus on optoelectronics, as it emerges as one of the most important engineering disciplines of the XXI century. Within optoelectronics, ultrafast superconducting optoelectronics is, in our view, the best approach to achieve hundreds-of-GHz operation speed and very-low-power dissipation input/output data links for digital electronics and advanced quantum communication systems.

III. Approach

Ultrafast phenomena, optoelectronics, and superconductivity are acknowledged fields of technological importance and a very large amount of research has been performed in these areas in recent years. Superconducting optical sensors find applications in various areas of optoelectronics and optical imaging. Short-visible, and mid-infrared optical radiation bands are especially important, since they correspond to the transmittance windows in the Earth atmosphere, thus, they are crucial for deep-space communications, as well as for effective satellite telecommunication and sensing. Optical fibers for the few- μm radiation spectrum with ultra low losses can also be fabricated and form basis for future advanced telecommunication systems. Contrary to current semiconductor optoelectronic compounds that lack adequately low bandgap values, superconducting photodetectors have essentially no bandgap limitations and exhibit uniform absorption within the entire IR-to-UV spectrum. The superconductor optical absorption also results in very large effective quantum yield of excited (hot) electrons. A single absorbed photon creates, through electron-electron (e-e) and electron-phonon (e-ph) interactions, an avalanche of secondary photoexcited carriers. As a result, the responsivity of superconducting photodetectors is significantly larger than even the best values for semiconducting photodetectors and avalanche photodiodes.

The unique optoelectronic capabilities of NbN photodetectors discovered by the MSPU-UR team were published in scientific literature, and presented at number of

invited talks, special lectures, and contributed conference communications. They were also subject of intense interest of high-tech trade journals, such as "Advanced Materials and Processes," "Laser Focus World," or "Photonics Spectra," who ran newsbreaks and feature stories on the prospects of NbN photodetectors as single-photon counters (see Appendix). NbN devices are the most sensitive and the fastest optical photon counters and should find practical applications in the areas ranging from satellite and deep-space optical communication, quantum cryptography, to ultrasensitive probing of integrated VLSI circuits.

IV. Results

IV. A. Scientific Results

During the period covered by this ONR/NICOP grant, we have conducted our research on optoelectronic time- and frequency-domain characterization of superconducting NbN hot-electron photodetectors and photomixers. In particular, we have performed time-resolved characterization of microbridge structures, patterned in high-quality, epitaxial NbN films, grown on sapphire substrates, using reactive magnetron sputtering. The microbridges were integrated into coplanar waveguide (CPW) lines with a 30- μm -wide center line and 5- μm -wide gaps to the ground planes. The CPW structures were covered with Ti/Au in order to improve their high frequency propagation characteristics. The superconducting transition T_c of the bridges was ~ 11 K. The experiments were conducted using a subpicosecond electro-optic (EO) sampling system designed by us. The microbridges were cooled below their T_c , current biased, and exposed to <100 fs optical pulses. The obtained experimental data agreed very well with the nonequilibrium hot-electron, two-temperature model. The quasiparticle thermalization time was ambient temperature independent and was measured to be 6.5 ps. The inelastic electron-phonon scattering time and the phonon escape time were fitted using the two-temperature model and were equal to 11.6 ps and 21 ps at 2.15 K, and 10(± 2) ps and 38 ps at 10.5 K, respectively. The obtained electron-phonon scattering time showed that the maximum intermediate frequency bandwidth of the NbN hot-electron phonon-cooled mixer at T_c could reach 16(+4/-3) GHz if one minimized the bolometric phonon-heating effect. The high frequency testing of NbN photomixers was performed in Moscow with the help of submillimeter and infrared continuous-wave sources and frequency beating measurements. In both the Rochester and Moscow experiments, the measured photoresponse was attributed to the nonequilibrium electron heating effect, where the incident radiation increased the temperature of the electron subsystem, while the phonons acted as the heat sink.

The conclusion of the above work was that the intrinsic ultrahigh (>10 GHz) speed of NbN devices make them an excellent choice for optoelectronic, photodetector-type interface for superconducting digital circuits, as well as for mixers for the terahertz regime.

We also showed that the quantum photon yield and responsivity of our NbN hot-electron photodetectors can reach the values of 340 and 220 A/W, respectively, for the infrared radiation with a wavelength of 0.79 μm . The above values are much higher than the corresponding parameters for any semiconducting photodetectors. The characteristics of the NbN photodetectors were presented within the general model, based on relaxation processes in the nonequilibrium electron heating of a superconducting thin film. The observed very high values of responsivity and sensitivity of our detectors were explained by the high multiplication rate of quasiparticles during the avalanche breaking of Cooper pairs.

Finally, our research lead to development of a novel superconducting single-photon detector for ultrafast counting of visible and infrared photons. Our devices consisted of ultrathin, 0.2- μm -wide, and 1- μm -long NbN stripes, maintained at 4.2 K and current-biased close to the critical current. The devices exhibited an experimentally measured quantum efficiency of $\sim 20\%$ for 800-nm photons and negligible dark counts. The research on NbN single-photon detectors continues (see Sec. V).

IV. B. Rochester-Moscow Collaboration

The co-PI's, Dr. Roman Sobolewski and Dr. Gregory Gol'tsman visited their partner institutions several times during the grant duration. Together, they established a detailed research plan and worked on the timely execution of the MSPU-UR collaboration. Mr. K. Iliin, a graduate student from MSPU spent 3 months in 1998 in Rochester, performing on-site, time-resolved characterization of NbN photodevices. On the other hand, a graduate student from Rochester, Carlo Williams, spent over 6 weeks in Moscow in 1999 working on fabrication of NbN photomixers. Finally, in summer of 1999, Dr. Alex Semenov from MSPU visited Rochester, conducting an extensive session of EO measurements.

Besides the scientific and research value, the ONR/NICOP grant provided much needed financial help for Russian researchers and allowed for the direct technology transfer from FSU to the US.

V. Transitions and Related Projects

The company Schlumberger Semiconductor Solutions from San Jose, CA, the world leader, and the largest producer of the CMOS VLSI testing equipment approached the UR-MSPU team and offered exploratory funding for developing practical single-photon infrared NbN photodetectors.

The team also received the NATO Linkage Grant, entitled: "Ultrafast Optoelectronic Signal Conversion Using Superconducting Photomixers and Photodetectors" (PI: Roman Sobolewski).

VI. Publications

List of manuscripts published under the ONR/NICOP sponsorship during the reported period:

BOOKS AND BOOK CHAPTERS

1. "Optical Sensors," (Chapter) R. Sobolewski and D. P. Butler, in: Handbook of Superconducting Materials, Institute of Physics Publishing Ltd., Bristol, UK (2002).

REFEREED JOURNALS AND PUBLISHED CONFERENCE PROCEEDINGS

9. "Picosecond Hot-Electron Energy Relaxation in NbN Superconducting Photodetectors," K. S. Il'in, M. Lindgren, M. Currie, A. D. Semenov, G. N.

- Gol'tsman, R. Sobolewski, S. I. Cherednichenko, and E. M. Gershenzon, Appl. Phys. Lett. **76**, 2752-2754 (2000).
8. "Infrared Hot-Electron NbN Superconducting Photodetectors for Imaging Applications," K. S. Il'in, A. A. Verevkin, G. N. Gol'tsman, and R. Sobolewski, Supercon. Sci. Tech. **12**, 755-758 (1999).
 7. "Ultrafast Superconducting Optoelectronics," (INVITED) R. Sobolewski, 1999-IEEE LEOS Meeting Conference Proc., IEEE Cat. No. 99CH37009 (Piscataway, NJ, 1999), pp. 631-632.
 6. "Characterization of the Electron Energy Relaxation Process in NbN Hot-Electron Devices," K. S. Il'in, G. N. Gol'tsman, B. M. Voronov, and R. Sobolewski, Proceedings of the 10th International Symposium on Space Terahertz Technology, 1999, pp. 583-591.
 5. "Quantum Efficiency and Time-Domain Response of Superconducting NbN Hot-Electron Photodetectors," K. S. Il'in, M. Currie, M. Lindgren, I. I. Milostnaya, A. A. Verevkin, G. N. Gol'tsman, and R. Sobolewski, IEEE Tran. Appl. Supercon. **9**, 3338-3341 (1999).
 6. "Comparative Study of the Bandwidth of Phonon-Cooled NbN Hot-Electron Bolometers in Submillimeter and Optical Wavelength Ranges," K. S. Il'in, S. Cherednichenko, G. N. Gol'tsman, M. Currie, and R. Sobolewski, Proceedings of the 9th International Symposium on Space Terahertz Technology, 1998, pp. 342-349.
 4. "Ultimate Quantum Efficiency of a Superconducting Hot-Electron Photodetector," K. S. Il'in, I. I. Milostnaya, A. A. Verevkin, G. N. Gol'tsman, E. M. Gershenzon, and R. Sobolewski, Appl. Phys. Lett. **73**, 3938-3940 (1998).
 3. "Picosecond Response of a Superconducting Hot-Electron NbN Photodetector," M. Lindgren, M. Currie, W.-S. Zeng, R. Sobolewski, S. Cherednichenko, B. Voronov, and G. N. Gol'tsman, Appl. Supercon. **6**, 423-428 (1998).
 2. "Fast NbN Hot-Electron Photodetector for Fiber Optics," A. A. Verevkin, K. S. Il'in, S. Cherednichenko, I. I. Milostnaya, G. N. Gol'tsman, E. M. Gershenzon, M. Lindgren, M. Currie, W.-S. Zeng, and R. Sobolewski, Proceedings of the 10th Joint Russian-German-Ukrainian Symposium on Superconductivity, N. Novgorod, 1997, pp. 112-121.
 1. "Picosecond Response of a NbN Hot-Electron Photodetector," M. Lindgren, M. Currie, W.-S. Zeng, R. Sobolewski, S. Cherednichenko, B. Voronov, and G. N. Gol'tsman, ISEC'97 Extended Abstracts, PTB Publ., Berlin, Germany, pp. 629-631 (1997).

INVITED CONFERENCE AND SEMINAR PRESENTATIONS

17. "Superconducting Ultrafast Photodetectors and Optical-to-Electrical Transducers," R. Sobolewski, presented at the International Conference on Applications of Optical Technologies, Photonics North 2000, Quebec, Canada, June 2000.
16. "Ultrafast Hot-Electron Superconducting Photodetectors," presented at The MITRE Corporation, Eastontown, NJ, March 2000.

15. "Ultrafast Optoelectronic Input-Output Interface for Superconducting Digital Electronics," presented during the 3rd ONR Workshop on Superconducting Electronics, Cape Code, MA, March 2000.
14. "Ultrafast Superconducting Optoelectronics," R. Sobolewski, presented at the 12th Annual IEEE Lasers and Electro-Optics Society Meeting (IEEE/LEOS'99), San Francisco, CA, November 1999.
13. "Hot-Electron Superconducting Photodetectors," presented at Schlumberger Automatic Test Equipment, San Jose, CA, May 1999.
12. "Ultrafast Superconducting Electronics," presented at the Department of Electronics and Information Techniques, Warsaw Technical University, Warsaw, Poland, April 1999.
11. "Prospects of High Temperature Superconducting Devices for THz/Infrared Electronics and Optoelectronics," presented at the Department of Electrical and Computer Engineering Graduate Seminar Series, University of Rochester, Rochester, NY, February 1999.
10. "Ultrafast Superconducting Electronics and Optoelectronics," presented at the Singapore Chapter of Electron Device Society Seminar Series and the Department of Electrical Engineering National University of Singapore, Singapore, January 1999.
9. "Hot-Electron Superconducting Photodetectors for Mid-Infrared Telecommunication," presented at the TRW Electronics and Technology Division, Space and Electronics Group Seminar, Redondo Beach, CA, February 1999.
8. "Hot-Electron Superconducting Photodetectors for Mid-Infrared Telecommunication," presented during the 2nd ONR Workshop on Superconducting Electronics, Bakersfield, CA, January 1999.
7. "Ultrafast Superconducting Electronics and Optoelectronics," presented at the School of Engineering and Applied Science Seminar Series, Southern Methodist University, Dallas, TX, November 1998.
6. "Superconducting Hot Electron Mixers for Fiber Optics," presented during the 1st ONR Workshop on Superconducting Electronics, Ridgecrest, CA, January 1998.
5. "Ultrafast Superconducting Optoelectronics," R. Sobolewski, Invited Lecture at the International Superconductive Electronics Conference (ISEC'97), Berlin, Germany, 1997.
4. "Ultrafast Superconducting Optoelectronics," R. Sobolewski, Invited Lecture at the Institute of Physics, Polish Academy of Sciences, Warsaw, Poland, 1997.
3. "Ultrafast Superconducting Optoelectronics," presented at the Laboratory for Laser Energetics, University of Rochester, Rochester, NY, August 1997.
2. "Hot Electron Superconducting Detectors and Mixers," G. N. Gol'tsman, Invited Lecture at the Lawrence Berkeley National Laboratory, CA, 1997.
1. "Hot Electron Superconducting Detectors and Mixers," G. N. Gol'tsman, Invited Lecture at the Smithsonian Observatory/Harvard University, MA, 1997.

VII. Patents

None.

material bounces back almost immediately, returning to its superconducting state within 40 trillionths of a second, or 40 picoseconds. The device works so fast because only electrons are heated up; the material's temperature remains very low. Such speed, combined with its small size and its ability to detect infrared light, gives the material potential as one component of a new type of computer known as a superconducting computer. The University of Rochester is one of three academic institutions in the country working on such technology.

The U.S. and Russian scientists involved in this project owe their collaboration to the U.S. Office of Naval Research, which sponsored the work in an effort to promote international cooperation among scientists in the post-Cold War era. The films were made and tested in Moscow, and the speed of the detector was measured at the University, whose engineers have long been known for their expertise in ultra-fast measurements.

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